Large Electrolysis Systems in Chemical Industry Challenges with the advent of Green Hydrogen Production

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Abstract – Electrolysis processes are a key factor in the chemical industry, initially for producing caustic soda (NaCl) with chlorine as a byproduct. With hydrogen production by electrolysis on the rise, this technology is attracting increasing attention.

Currently, the predominant rectifier technology in the high current area is based on thyristor controlled 3 phase bridges which has been a mature technology for decades but creates challenges regarding harmonics and power factor control, especially under constantly changing operating conditions like fluctuating availability of green energy.

New technologies based on IGBT semiconductors in active frontend or chopper designs line up to take over. These technologies provide solutions for the challenges of the pure restriction on the use of green energy only, the type of these green grids and the power quality issues that come with the operation of large rectifier systems.

The paper will describe some aspects as they were faced and tackled during the execution of a large project in the range of 2600MW electrolysis load. A hypothetical hydrogen supply for green steel production is sketched.

Additional challenges in the downstream production of Ammonia and/or Methanol due to replacement of steam turbines by large electrical drive systems are addressed.

Index Terms — Green hydrogen production, rectifier technologies, grid issues, increase in electrical loads.

I. INTRODUCTION

With the invention of the first battery by Alessandro Volta began research into the effects of the “new” electrical current on chemical matters. The English scientists W. Cruikshank and H. Davy showed that the new electrical current from a Volta battery could be used to segregate chemical matters by electrolysis, namely the production of caustic soda. The production of chlorine was first observed by Simon.

But due to the very limited availability of electricity from a Volta Battery, these investigations were more of theoretical nature and limited to laboratory experiments rather than production in larger industrial scales.

This changed with the upcoming of DC generators, mainly developed by Werner von Siemens, in 1866/67. The world’s first larger scale industrial chlorine electrolysis was commissioned in 1890 in Griesheim near Frankfurt. For this, as a DC source, dynamo machines for 1000A at 60V were developed by company Schuckert Gleichstrommaschinen (DC machines), driven by steam engines from company Gebrüder Sulzer in Winterthur with steam boilers from company Steinmüller in Gummersbach.

All these companies, or their successors, are well known in the industry and remain in operation today.

Electrolysis developed into an essential technology for industrialization, particularly as a source to produce caustic soda and chlorine. From the beginnings with 1000A at 60V; up to >300 kA units at 300V for amalgam electrolysis plants. With the upcoming of much more environmentally friendly membrane electrolysis plants the chlorine production goes down to electrolyzer units in the 18kA and 600V range which are paralleled to achieve the requested final capacity.

With the challenges of decarbonization, large-scale production of hydrogen (H2) by electrolysis emerges as a completely new field of industry. To become “green”, these electrolysis plants need to be fed by renewable energy sources. By this, electrolysis becomes a new key technology to produce hydrogen, which was until recently mainly produced by steam reforming from natural gas, a process which is a large CO2 contributor.

II. USE OF HYDROGEN

Within the chemical industry and industrial process technology, hydrogen is one major component used in a variety of large processes, just to name a few:

- Hydrogen is one key ingredient in the ammonia and methanol production for fertilizers and other chemical base products and is further used in refineries for processing mineral oil.
- In the future, hydrogen may play a major role in the production of steel. For this, the currently predominantly used process is the conventional smelter process with blast furnaces and blast oxygen furnaces. For steel to become environmentally friendly it must be produced with the direct reduction process, which requires huge amounts of hydrogen.
- As hydrogen in its pure form is rather difficult to transport, it will be required to embed it into easier to transport media – one of these being ammonia. So, beside the above-mentioned production for fertilizers, ammonia as a transport medium for hydrogen may become a new standard. Ammonia could potentially become the new gasoline. R&D work is ongoing to modify combustion engines, mainly for the replacement of crude oil in ship propulsion by direct combustion of Ammonia. In addition, cracking technologies are being refined to extract the hydrogen from ammonia.
- When we talk about environmental decarbonization, one major factor is the replacement of hydrogen produced by steam reforming from natural gas, with hydrogen

produced by electrolysis, which is fed by electrical power, preferably generated by renewable sources such as wind, photovoltaic or hydroelectric power plants.

- The various processes for the production of hydrogen are often explained in a scheme of colors.

	Terminology	Technology	Feedstock/ Electricity source	GHG footprint*
PRODUCTION VIA ELECTRICITY	Green Hydrogen	Electrolysis	Wind | Solar | Hydro Geothermal | Tidal	Minimal
	Purple/Pink Hydrogen		Nuclear	
	Yellow Hydrogen		Mixed-origin grid energy	Medium
PRODUCTION VIA FOSSIL FUELS	Blue Hydrogen	Natural gas reforming + CCUS Gasification + CCUS	Natural gas | coal	Low
	Turquoise Hydrogen	Pyrolysis	Natural gas	Solid carbon (by-product)
	Grey Hydrogen	Natural gas reforming		Medium
	Brown Hydrogen	Gasification	Brown coal (lignite)	High
	Black Hydrogen		Black coal	

*GHG footprint given as a general guide but it is accepted that each category can be higher in some cases.

Fig. 1: Hydrogen color scheme, [1]

- This paper deals with the pure green hydrogen technology, in which the electrolysis is operated with purely renewable electrical energy.
- When we talk about the decarbonization of the hydrogen production, it's important to first get an overview about the relevant quantities.
- Currently, the overall H2 production in Germany is about 1.7 Mio tons / year, mainly based on steam reforming from natural gas, shown as "grey" in the above Fig.1. This amount is used for further processing in the chemical industry and for fertilizer production.
- An additional substantial amount of hydrogen will be required, if the steel production will be converted from conventional smelter to direct reduction, more details to this in chapter IX.
- In addition, a much larger amount of H2 will be required to make the economy more environmentally friendly. These amounts are constantly changing and are significantly higher than the 1.7 Mio tons / year mentioned above.

III. Basics about Electrolysis

As per Michael Faraday's laws, the mass (m) of a substance produced at an electrode is directly proportional to the charge (Q; with the SI unit coulombs or ampere seconds).

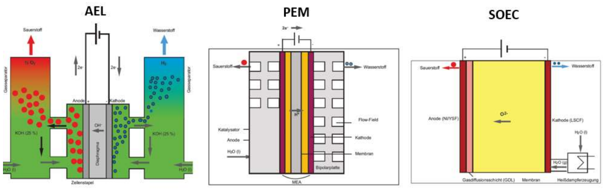
m prop to Q ➔ m/Q = Z

As can be seen from the units of measurement, the electrolysis output depends only on the magnitude of current and the material dependent proportionality factor Z.

The required voltage for the electrochemical reaction can be derived from the electrochemical properties of the used materials and process/electrolyzer characteristics.

When we talk about hydrogen electrolysis, there are currently three major electrolyzer technologies for hydrogen production plants on the market, with different levels of maturity.

- **AEL** - Alkaline (Water) Electrolysis
- **PEM** - Proton Exchange Membrane
- **SOEC** - Solid Oxide Electrolysis Cell also known as High Temperature Electrolysis



	AEL	PEM	SOEC
Kathode	$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$	$2H^+ + 2e^- \rightarrow H_2$	$H_2O + 2e^- \rightarrow H_2 + O^{2-}$
Anode	$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$	$H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$	$O^2 \rightarrow \frac{1}{2}O_2 + 2e^-$
Gesamtreaktion	$H_2O \rightarrow H_2 + \frac{1}{2}O_2$	$H_2O \rightarrow H_2 + \frac{1}{2}O_2$	$H_2O \rightarrow H_2 + \frac{1}{2}O_2$

Fig. 2: Different electrolysis technologies, [2]

To our knowledge, the large scale electrolyzer technologies in the range of 10+MW per electrolyzer are currently only available for the AEL and PEM technology.

Fig. 3 shows two AEL electrolyzers in the 20MW range. This is the rating that was used in the executed project and example described later:

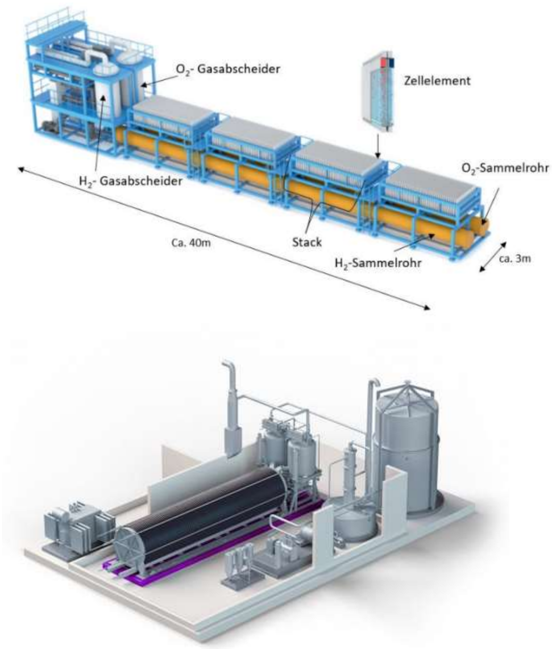


Fig. 3: 20MW AEL Hydrogen electrolyzers, [3, 4]
technical ratings and performance data can be found under [5]

A good overview about the status (as of 2022) on electrolyzer technologies can be found in [5]

IV. High Currents and Electromagnetic Fields

As per the electrotechnical theory, each conductor that carries an electrical current is surrounded by a magnetic field. This is true for DC currents which produce a constant field, as well as for AC currents which produce an alternating magnetic field and can be observed in our daily lives when we come close to electrical conductors. In our normal lives and environments this is not a problem for humans. The easiest way to demonstrate such a field is the well-known school experiment with a magnetic needle that is deflected when placed near a current carrying conductor.

The situation becomes more critical when humans are exposed to strong magnetic fields caused by AC currents.

And this is the case when we talk about electrolysis installations, where, in our case, currents in the range from 3kA up to 100+kA (for old mercury electrolysis cells) are present.

But electrolysis uses DC rather than AC, so where is the problem? The electrolysis current is DC, but the rectified current contains an AC portion, known as ripple, which varies depending on the rectifier technology used. Because the ripple is purely AC, it generates an alternating magnetic field. In recent years, norms and standards regarding a safe work environment have been developed, including the EG Guideline 2003/18 and the ICNRIRP Guideline, which address maximum exposure to magnetic fields at work. These norms define limit values for alternating fields. Such fields also affect the cell room, where all electrolyzers are installed.

This type of calculation is carried out by specialized institutes and requires very detailed information about the geometry of the electrolyzer, its bus bar routing, and the overall arrangement with regards to maintenance and operating spaces. In addition, electrical data about the selected rectifier, electrical characteristic of the electrolyzer (inductivity, resistivity, capacitance), the expected operating currents and its DC ripple (usually to be provided by the rectifier vendor) needs to be provided.

In our cases, based on the first results, we had to optimize the routing of the DC busbar of the electrolyzer. The following Fig. 4 shows a field distribution of a row of electrolyzers within a cell room. The red areas show high fields, where the limit values are violated. However, these areas are out of reach of the operating personal (personal cannot enter during operation) or the person only passes the area with parts of the body, like feed and lower legs. and hence the design was approved.

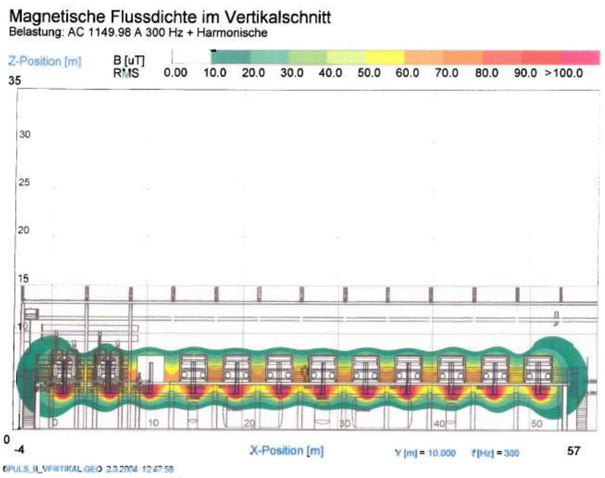


Fig. 4: Magnetic flux density in vertical cross section, 6-pulse rectifier [6]

V. Main Components for Electrolysis Technology

A. Rectifier

The currently predominant technology for large current rectifier systems in the high kA range is based on rectifier systems with thyristor or SCR.

These rectifiers are nowadays mostly built as a so-called B6 bridge as per IEC denomination, see Fig. 5. These configurations can be easily built up to 1000V and in the high kA range of 100kA per unit and more. To achieve the higher end of the range, it will be necessary to line the SCR in series for higher voltages, or to parallel them to achieve higher currents than that the individual device can support.

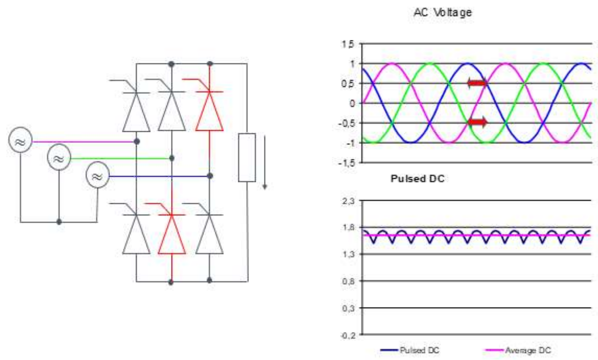


Fig. 5: B6 bridge rectifier with SCR [6]

The voltage, and hence the subsequent current flow, can be easily controlled by delaying the firing angle of the thyristors from 0 to 180 degrees.

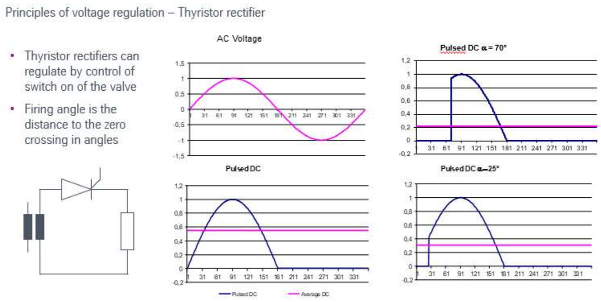


Fig. 6: Voltage variation by delayed firing angle [6]

As nice as this appears, it comes with a significant drawback. When the thyristors are controlled over such a wide range, the resulting harmonics and demands on reactive power are tremendous, causing numerous problems for the supply grid. Large filter units and capacitor banks for power factor improvement will be required.

Without going into too much detail, the following gives a short introduction into the theory about harmonics and the power factor of a B6 rectifier configuration.

When voltage and current flow are not in line with each other we have a demand on reactive power. This is well known from inductances (delayed current flow) and capacitances (delayed voltage build up). A similar effect occurs when a thyristor is not fired simultaneously with the voltage zero crossing but delayed by a firing angle. See Fig. 6 above. We will also see a demand for reactive power, similar to that of an inductance. The larger the firing angle (later firing from voltage zero crossing), the larger the reactive power demand. A first step in reducing the reactive power demand is to limit the firing angel to about 30° instead of controlling the voltage over the full range of 180°.

This can be supported by installing an OLTC (On-load tap changer) on the transformer. This allows us to achieve a coarse (in steps) control of the voltage magnitude without reactive power demand. For a further fine control, we now just have to control the voltage on a small steps range (from the OLTC). This can be achieved by small firing angles of up to approximately 30-40°. Theoretically there would be no reactive power if the firing angle is 0°, say in line with the voltage zero crossing. However, there is still a certain amount of reactive power due to inductances in the feeding grid and the transformer windings.

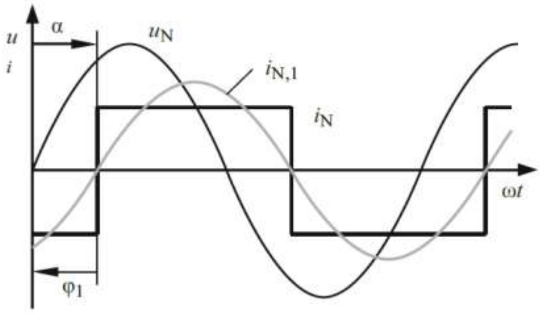


Fig. 7: Supply voltage and current for ideal rectifier [2]

The operation of bridge type rectifiers always results in distortion of the feeding voltage. The reason for this is twofold. First, when the current flow is transferred from one thyristor to another, it always coincides with a limited line-to-line short circuit in the feeding grid. This is called commutation.

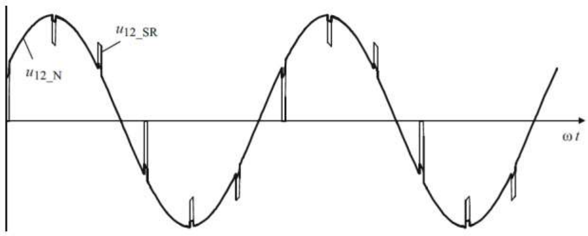


Fig. 8: Commutation dips of supply voltage for a B6 bridge rectifier [2]

Second, as can be further seen on Fig. 7, the transformer primary current has a non-sinusoidal form.

As per the well-known Fourier Analysis, it is possible to define any periodic curve form by an infinite number of sinus curves with different frequencies and amplitudes. The sinus curves that differ from the base curve are called harmonics. The forming law of harmonics for a B6 type bridge rectifier is

v = k * p +/-1 with v = order of harmonic,
k = 1, 2, 3, …
p = number of pulses,
6 for B6 bridge,

With this, the theoretically produced harmonic currents for a B6 bridge type rectifier are of 5, 7, 11, 13, … order.

The order of produced harmonics is only dependent on the number of pulses and, hence, the type of rectifier. The magnitudes of the produced harmonics are theoretically as per

In = 1/n * I1

All of this is pure theory. In reality, there are also fractions of non-characteristic harmonics which must be considered.

The following figure shows a „real world“ tabulation for a 12-pulse rectifier configuration, based on information from two different vendors. The main reasons for these imperfections are in the slight variances in the transformer design, where a winding cannot be manufactured exactly according to theory.

Harmonic	I_v/I_1 [%]			
v	Theorie 6p	Theorie 12p	Vendor A	Vendor B
1	100,0	100,0	100,0	100
5	20,0	-	2,6	0,956
7	14,3	-	2,0	0,654
11	9,1	9,1	7,1	7,285
13	7,7	7,7	6,0	5,615
17	5,9	-	1,0	0,167
19	5,3	-	0,9	0,127
23	4,3	4,3	2,6	1,336
25	4,0	4,0	2,1	0,9
29	3,4	-	0,5	0,016
31	3,2	-	0,5	0,01
35	2,9	2,9	1,4	0,377
37	2,7	2,7	1,2	0,449
41	2,4	-	0,4	-
43	2,3	-	0,4	-
47	2,1	2,1	0,4	0,434
49	2,0	2,0	0,4	0,382

Fig. 9: Theoretical vs. real harmonics of a 12 pulse, B6 rectifier [2]

These harmonic currents are fed back into the feeding grid, where they produce distorted voltage profiles across the grid impedances.

International standards like IEC 61000-3-2, IEEE 519, IEEE 3002.8 provide guidance on how to calculate and assess them, whereas individual national grid code standards issued by the grid operators stipulate limits which must be complied with when connecting and operating this type of consumers on the grid. As explained above, to reduce this problem, common practice is to install an OLTC in the feeding transformer, which will make a coarse regulation of the voltage without disturbing the grid. The thyristors will then only be operated in a range of approximately 10 – 40° which considerably reduces the grid impact.

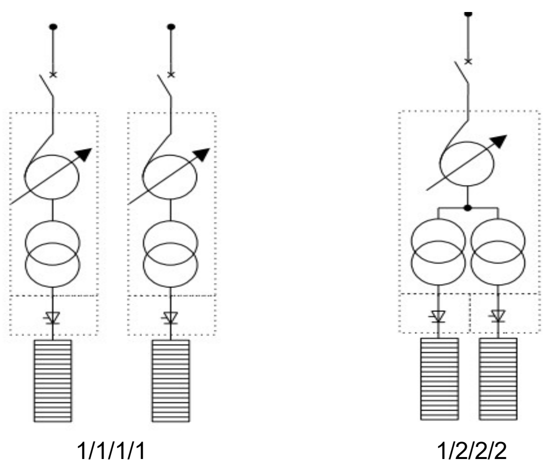


Fig. 10: Transformer / Rectifier Electrolyzer set-ups [6]

Fig. 10 shows further improvements. The left side requires an individual HV feeder (range 30 to 70kV, depending on system setup) for each transformer rectifier system. The arrangement displayed on the right combines the two transformers and one autotransformer with OLTC in one tank, but still feeds two 6 pulse rectifiers. This reduces the amount of HV feeders. The two rectifier transformers are secondary side delta and wye, which further improves the harmonic spectrum from 6-pulse feedback to 12-pulse feedback at the primary connection point, as can be seen Fig. 11.

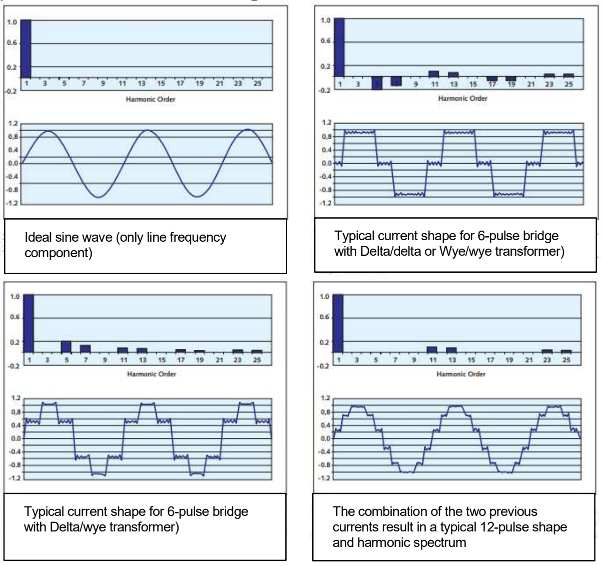


Fig. 11: Current composition and harmonic spectra [7]

It must be kept in mind that the 12-pulse feedback to the grid is only valid if both rectifiers are operated with the same firing angle. This puts a certain limitation on the individual control of each electrolyzer. Based on the overall quantity of electrolyzers, judgement must be made whether this is sufficient for a fine control of the process. The labeling 1/1/1/1 describes the quantity of main components, i.e. 1x autotransformer with OLTC / 1x rectifier transformer / 1x rectifier / 1x electrolyzer.

Another rectifier technology on the market is based on pulse width modulation (PWM) and is realized with IGBT choppers as shown below.

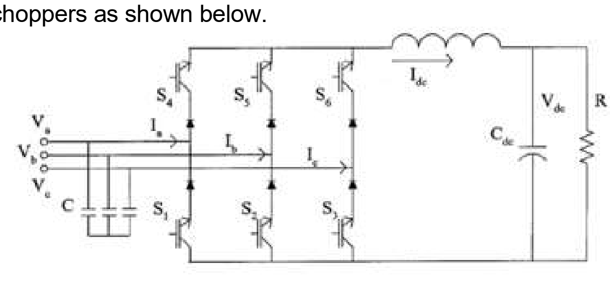


Fig. 12: Principal of a DC rectifier with IGBTs [2]

The advantage of the IGBT is that via the PWM it can control the on and off status of a valve, whereas the SCR can only control the on status. For switching off, the SCR must wait for the natural zero crossing of the voltage.

The very positive side effect is that the harmonic injection towards the feeding grid is much less and can be easily controlled by an active front end bridge. All this reduces the scope of harmonic mitigation measures and PFI.

However, there are currently also some disadvantages with this technology. Current IGBTs have a much less current carrying capacity than SCR, which results in a lot of parallel components. In addition, the control of a IGBT system is much more complex. As per our knowledge, the maximum load of a full bridge IGBT system is currently about 10MW for commercially available products. Especially the higher currents as required by the AEL electrolyzers cannot be provided as of now. For this reason, we have not elaborated more on this topic, although a lot of development work on this technology is being done.

Challenges on this topic are the high harmonic and reactive power demand and the associated filter technologies for fast acting, due to fast changes in energy availability as well as individual electrolyzer operation.

B. Transformers

To accommodate connection to the supplying grid voltage, each of such a rectifier is connected via a special type of rectifier transformer in a Delta/wye or Delta/delta winding configuration. Depending on the total number of required rectifiers, a single, double or maximum triple transformer may be designed. Here, one, two or three transformers are installed in one tank.

Often, for coarse adjustment of the voltage, an autotransformer with OLTC is installed in the same tank as an incoming device.

Single and double transformers are state of the art and frequently manufactured. A triple transformer may present challenges because the transformer core, the segregation of windings, and particularly the high current outfeed may be difficult to build in the same tank. It must be kept in mind that the output current of a rectifier transformer is in the range of 25+kA. This is substantially higher than that of a distribution transformer. This type of current outlet with its large cross sections via massive copper or aluminum bars requires special attention for routing and penetration through the tank walls.

Fig. 13: 55MVA rectifier transformer, secondary outlets for two 6-pulse rectifiers [6]

Challenges of the transformer design are not too critical; the handling of high currents and associated eddy currents on the secondary outlets is well known; however, not every transformer manufacturer has experience with these designs. A second, far more serious issue is the manufacturing capacity for these large transformers. For large projects, the quantity can easily exceed 10 units, which must be delivered in a relatively short time frame.

C. *Power Factor and Harmonic Filter issues*

As previously stated, large rectifier systems place a significant demand on reactive power and are an important source of harmonics, both of which burden the supply grid. In the traditional world, with constant and ample supply power and the desire for most of time full load operation over long time periods, this was manageable by installing fixed capacitor sets, perhaps in two or three steps, for power factor improvement (PFI) and a couple of tuned filters for the most severe harmonics, mainly the first orders 5, 7, 11, 13. These devices were switched on when the process was stable.

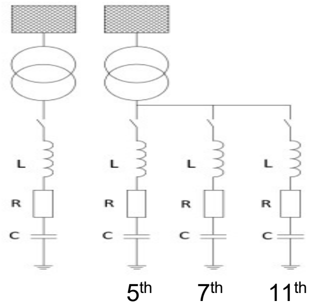


Fig. 14: Harmonic filters, tuned and switched [2]

Adaptation to changing conditions was only necessary when the process was ramped down or electrolyzers were turned off, which occurred rather infrequently.

This is somewhat different with the new world of renewable energy supply, where there is a constant change in the amount of supplied energy due to variations in the renewable resource like solar irradiation or wind. Because these resources will constantly vary in predictable as well as in unpredictable ways, it will be necessary to adopt the PFI as well as the harmonic filters often and quickly.

This is not so easy with the conventional PFI system, mainly consisting of switched capacitor banks, as each switch off requires a certain waiting time until the unit can be switched on again. This waiting period may be too long to comply with the requirements. Using thyristor-controlled reactors (TCR) and thyristor switched capacitors (TSC) is one way to overcome this.

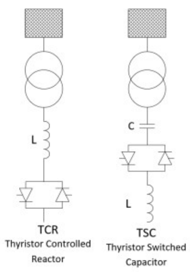


Fig.15: TCR and TSC for PFI control [2]

As these devices are also SCR controlled, they generate disturbances of their own, increasing in this way the burden and interactivity with the harmonic filters.

The same is true for the adaptation of the harmonic filters as a result of changes in load adjustment of the electrolyzers in line with changing energy supply. This may be caused by the cessation of wind or clouds that reduce solar irradiation. Again, fixed step filters may not be possible, and switching to electronic devices such as static synchronous compensator (STATCOM) is a valid option.

A STATCOM is a power electronic device, based on IGBTs and PWM control. Such a device can generate currents of any waveform and frequency and is therefore well suited to compensate harmonic currents by adding currents with the same amplitude but opposite direction. In addition, it can also contribute to the improvement of the PFI. The STATCOM will be connected to the feeding bus and act as a current source. It does not provide active power and thus does not require an energy source but only a capacitor for intermediate storage.

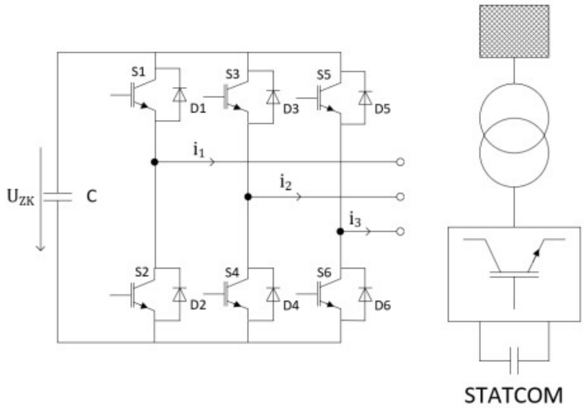


Fig. 16: STATCOM in B6 configuration [2]

The challenge in designing these systems is to quickly adapt to the availability of energy resources, the required technology and the proper integration into the overall system, which consists of PV parks, wind farms, and the connecting transmission lines. Whatever system is chosen, the amount of space for capacitors, inductors and/or electronic cabinets is not neglectable and must be considered in the overall system layout.

D. *System set-up*

This basic set-up as per Fig. 9 for one or two electrolyzers must now be extended to larger numbers of electrolyzers, as will be required for production purposes. Constraints are the supply voltage and the commercially available switchgear.

As a rule of thumb, the following can be assumed. A 20MW electrolyzer requires about 22MVA transformer rating. Assuming an efficiency of 97% and a PF of 0.87 (worst case, before compensation), operating such a 1/1/1/1 arrangement connected to a primary supply of 33kV will draw about 480A from the switchgear. Subsequently, a 1/2/2/2 arrangement will require about 960A. Due to overall cost savings for the transformer / rectifiers as well as for the feeding switchgear system, the 1/2/2/2/ configuration was selected as the basis for execution.

As of today, the commercially dominant, maximum available operating current for switchgear in the 30 – 70kV range is 3.150A, with some exceptions towards 4.000A. This will result in a basic arrangement for one switchgear as shown in Fig. 17. By using a higher supply voltage of, for example, 66kV, the current demand for 2 electrolyzers is approximately 50% of the 33kV system. The system is similar to that shown in Fig. 17, without tie breaker and with one transformer only. It must be kept in mind that the cost for 66kV switchgear and breakers are higher due to the now applied high voltage technology versus the medium voltage technology on the 33kV level.

The afore mentioned power factor improvement and filter equipment is also shown and must not be neglected in rating and space requirements.

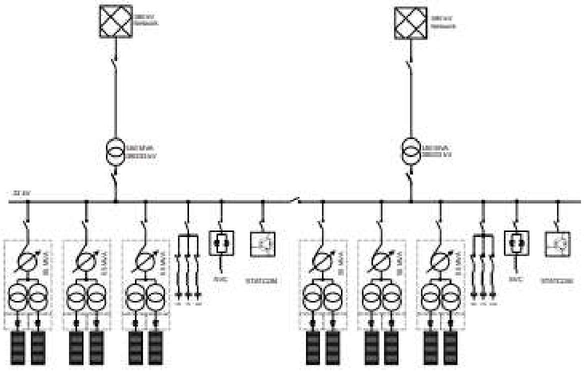


Fig. 17: 1/2/2/2 set-up on a 33kV switchgear [6]

E. DC Switches

The nature of DC and especially high currents makes it very difficult, and in our current magnitude of 30kA+ almost impossible to switch these currents. The difficulty arises from the lack of a natural zero crossing of the voltage, as with AC, and thus the large and strong arc that will be produced during the opening of contacts. Nonetheless, an electrolyzer must be disconnected from the DC source, even when in operation. This is accomplished by controlling the rectifier by interrupting the firing pulses of the thyristors. This reduces the current flow through the electrolyzer to zero. Now it is possible to open a switch without producing a disastrous arc. However, due to battery effects, small “battery currents” from the electrolyzer continue to exist, but they can be easily interrupted by use of pre-contacts, which can be replaced after a number of operations. After opening the main contacts, the pre-contacts can be safely opened and the electrolyzer is isolated from the source.

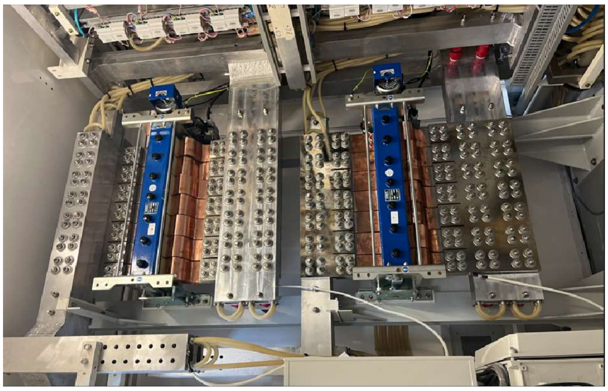


Fig. 18: DC isolator switch, 35kA [6]

Challenges with DC switches stem from their unique design, which limits the number of potential vendors. Another critical point may be the production capacity of these vendors. It should be noted that each electrolyzer requires two of these DC switches, one for the minus and one for the plus connection.

VI. Feeding Power Grids

A. Conventional power grids

These grids are fed by rotating synchronous generators, driven by steam or hydroelectric turbines. These generators are a huge mechanical rotating mass, which tries to keep the speed constant, even in case of short circuits. This results in the well-known short circuit contribution of generators within the first moments after a short circuit.

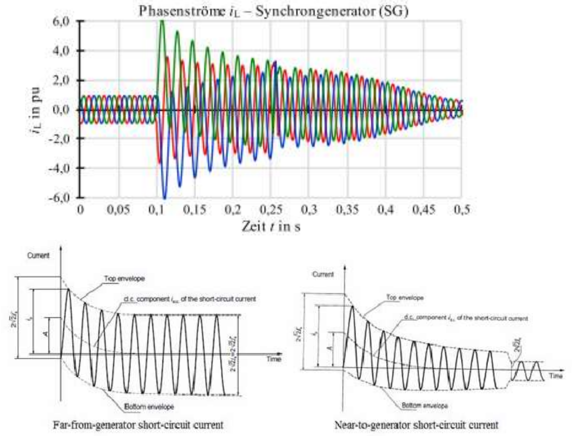


Figure 6. IEC-60909 short-circuit types [2]

Fig. 19: Short-circuit currents from synchronous machines, far and near generator [8], [9]

This behavior is well investigated and considered in the various international standards for grid stability and short circuit calculation.

As a result of the rotating mass of generators, the initial short circuit Ik” is substantially larger than the nominal current of the generator. This is well considered in the protection settings of the generators as well as in the overcurrent protection for the connected equipment.

This behavior also describes the short circuit power which is an important feature of a feeding grid.

The higher the short circuit power of a grid, the less vulnerable it is to the detrimental influences of harmonics, introduced by power electronic equipment such as SCR controlled rectifiers.

Another source of rotating mass and energy are smaller wind turbines driving asynchronous or double fed asynchronous generators. These generators are built up to a power range of 1,5 – 2MW. Asynchronous generators have a similar behavior and contribution to short circuits as asynchronous motors and thus contribute only to the initial short circuit current. In contrast, double fed asynchronous generators also contribute to the permanent short circuit current.

B. Purely renewable energy grids

These grids only comprise of wind turbines, PV parks and hydroelectric generators. With the anticipated demand of wind power to meet the needs of the green transformation, wind turbines have been developed to larger capacities, and the rating of an individual machine is now 8MW or higher, particularly for offshore installations. This is more of a challenge for the tower and the rotor blades than for the generator. Especially transportation for these large components is a challenge and may only be possible for offshore rather than onshore installations. Just as an example, the rotor blades of a 6MW wind turbine reach already a length of 65m.

The size and rating of wind turbine generators has made tremendous progress over the last 40 years, as shown in Fig. 20. They started with about 30kW and are now at

12MW, approaching the 15MW rating for offshore turbines. The rotor blades in this range will be more than 100m long.

Wind turbines used to support the industrial transition to a green energy base will most likely fall into this high-power category.

	1980	1985	1990	1995	2000	2005	2015	2020
Max. Nennleistung (kW)	30	80	250	600	1.500	3.000	7.000	12.000
Max. Rotordurchmesser (m)	15	20	30	46	70	90	130	220
Überstrichene Rotorfläche (m²)	177	314	707	1.662	3.848	6.362	13.273	38.000
Max. Nabenhöhe (m)	30	40	50	78	100	105	150	150
Max. Jahresenergieertrag (MWh/a)	35	95	400	1.250	3.500	6.900	15.000	67.000

Werte für Anlagen onshore und offshore

Fig. 20: Development of wind turbine ratings [10]

In this high-power range, they comprise either of synchronous or asynchronous type generators, but in any case, are always connected via an electronic converter to the grid.

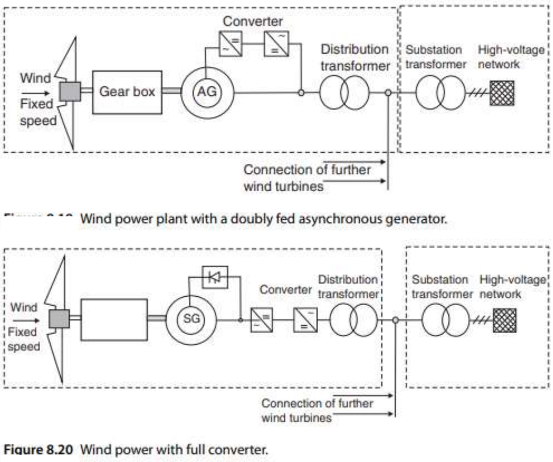


Fig. 21: Generator systems for large wind turbines [11]

In the case of short circuits, these electronic converters act like a controlled current source with an infinite parallel impedance.

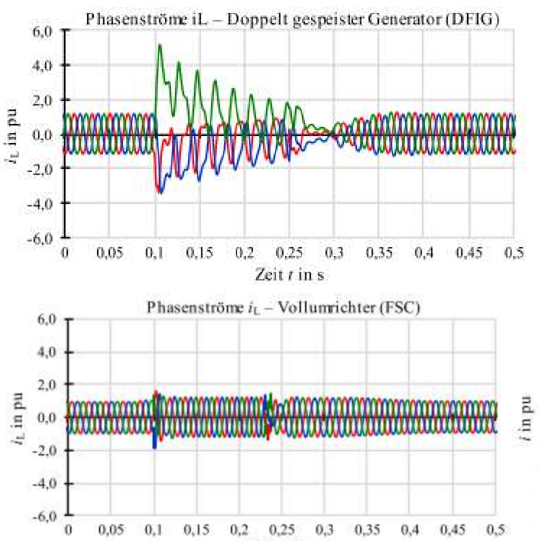


Fig. 22: Short-circuit currents from converter connected wind turbine, top DFIG, bottom converter connected synchronous generator [8]

There are no DC components, like in the conventional synchronous generator, and the short circuit current is only slightly larger than the rated current due to the limiting effect of the converter. This requires a completely new thinking regarding grid behavior and protection settings. Furthermore, the grid short circuit capacity is significantly lower than in a conventional grid, which again leads to challenges regarding the effects of harmonics.

With the connection via converters, in a purely wind turbine-driven grid, the sinusoidal voltage is created by electronic means rather than spaced rotating magnetic field, as in synchronous generators.

Another major contributor in renewable energy grids are PV parks. As for the afore mentioned wind parks, these PV parks are connected via converters to the grid. Again, the sinusoidal grid voltage is created by electronic means instead of rotating synchronous generators. The resulting short circuit currents are again rather small and only marginally larger than the rated current of the converters.

Except for really large hydroelectric power plants like for example Itaipu in Brazil, the contribution to large scale hydrogen electrolysis may be limited, as free generating capacities in the high MW range may be seldom, see examples under chapter Applications. However, hydroelectric power plants with standard rotating synchronous generators contribute to short circuit currents and short circuit capacity through their standard behavior, similar to steam turbine-driven generators, but are rarely used in conjunction with the other two.

C. Mixed power grids

This type of grid is currently the most common in green technology, particularly during the transition in highly industrialized countries with strong conventional grid systems. They come up with the increasing capacity of renewable sources connected to existing conventional grids, such as offshore windfarms that are connected to the mainland via DC links.

D. Availability of renewable energy

It is well known that the production and consumption of electrical energy must always be balanced. Except for special cases, such as pumped storage power plants, electrical energy cannot be stored and must be consumed at the time it is generated. In conventional grids this is achieved by ramping up and down the power plants by increasing or decreasing the fuel supply.

Essentially, this is also true for renewable energy grids, with the exception that the supply is dependent on non-influenceable “fuel” supply. When the sun goes down, there is no PV and when the wind weakens, wind power decreases. Hydroelectric plants may be the only renewable source that can be controlled. But, as previously stated, their contribution on a larger scale is relatively small.

For sudden changes and stabilization of the grid, large Battery Energy Storage System (BESS) in the high MW range may be installed. But using these BESS as a full replacement in case of simultaneous absence of light and wind appears not to be feasible.

The only way to keep such a renewable grid stable and operational is to constantly and quickly modulate the load, such as a chemical process powered by renewable energy.

In a purely renewable grid only consisting of PV, wind and hydroelectric, this is a mandatory physical requirement.

In a mixed grid, fluctuations in renewable power could be compensated by the increase of fuel supply to the conventional sources. However, this would contradict decarbonization goals and efforts.

To address this issue, the chemical process, in our case the electrolysis plant as well as the downstream processes, must be adjusted to match the energy availability. This adds to the burden on process plants, which were originally designed to operate at rated capacity rather than be ramped up and down.

It is also a challenge for setting up operating regimes for the electrolysis, such as deciding which electrolyzers to ramp down, maintain, or shut down. Another critical operational decision is how to deal with a sudden loss of generation capacity like tripping of a windfarm or PV transformer in the range of 100 or 200MW.

Another important factor in this regard is the filter and PFI equipment's very flexible operation and integration into renewable grids, as it brings together various types of power electronic equipment: rectifier systems, harmonic filter and PFI systems, and converter-connected PV and wind generators.

E. Ride through capability

Fairly new to electrical trade in the chemical industry is the ability of the plant to cope with grid disturbances, particularly the so-called Fault Ride Through (FRT) situations. FRT considerations are historically defined as a characteristic of power generation plants.

Nevertheless, due to the huge size of actual electrolysis plants in terms of power, especially hydrogen electrolysis plants, focus comes up to the behavior of these plants regarding FRT situations.

Main topics in this regard are High Voltage Ride Through (HVRT) and Low Voltage Ride Through (LVRT). With regards to network stability, the LVRT is the most critical one.

Fault ride through capability describes the ability of an electrical power generation system to respond with a certain reaction to disturbances of the electrical power network. Typically, the disturbances arise from network faults followed by sudden voltage changes of a limited duration. Relevant curves are laid down in standards or grid code documents, see Fig. 23.

Typically, two cases are defined for fault ride through situations, LVRT (Low Voltage Ride Through) and HVRT (High Voltage Ride Through.

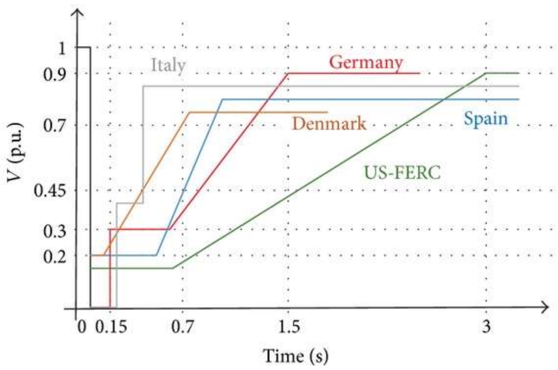


Fig. 23: Requested voltage reoccurrence after a fault as per various national grid codes [6]

Assuming a network fault such as a line short circuit, it is followed by massive current flows to the place of the fault until the fault is cleared by the network protection system. Typical fault clearing times are assumed to be 150 ms. Starting from the fault point, the grid voltages are disturbed in the form of a funnel. To keep the network in stable condition and to limit the expansion of the voltage funnel, additional reactive power must be supplied to the network. In classical networks this reactive power has been provided by the synchronous machines in the centralized power plants.

In modern networks with increasingly decentralized power generation and a high degree of power electronic controlled generation units, the provision of the required reactive power must be supported by the decentralized power generation units.

Without going into too much detail, the requested response time may be easily complied with by the rectifier system. But further challenges may arise from the chemical process. If pumps drop out due to a short-time power outage, it may take too much time to restart them without violating other process conditions, such as flow or pressure, which cause a process shutdown. Such a process shutdown can bring another critical situation to the grid, as large amounts of MW loads are suddenly disconnected, and the supply must be ramped down to maintain grid voltage and frequency. Further investigations, also from a process perspective, may be required to make the process more robust.

VII. ELECTRICAL PLANT INFRASTRUCTURE

An electrical infrastructure for a chemical complex is already a challenge and comprises the full scope of electrical engineering and components such as

- Power transformers for connection to the grid
- Switchgear in the medium and high voltage range
- Distribution type transformers of various ratings
- Electric Motors from fractional kW to MW rating
- Adjustable speed drives from kW to MW range, rarely in the high MW range
- Extensive cable networks
- Sometimes generators in the MW range

By adding the needs for a large-scale electrolysis plant, this scope further increases by

- Additional MV switchgear in the 30 to 70kV range
  - Each rectifier for an electrolyzer needs its own feeder, twin or triple units, as described above, may reduce this number
- Large number and scale of filter and power factor improvement installations
- Large number of specialized rectifier transformers each ranging from 25 to 55MVA, depending on single or twin arrangement of the rectifiers, see Fig. 13
- Large number of rectifier systems, usually installed in container type housings, see Fig. 24
- If this electrolysis plant is part of an ammonia or methanol complex, additional "new" electrical consumers must be considered, replacing the steam turbine drives used in conventional technology. These motors may be drive-systems or constant speed, but they are undoubtedly in the high MW range and may require special attention regarding the start-up

Fig. 24: 2x 16kA rectifier in container housing [6]

As with electrolysis, these downstream process plants must be modulated to match the availability of the renewable energy source. As it is not always possible to modulate down to small loads, storage systems for the feedstock (hydrogen) may be required. Another new, large consumer within an ammonia plant is the Air Separation Unit (ASU) which supplies the required nitrogen. This ASU can easily require high MW on electrical power for the compressors.

Depending on the capacity of such an ammonia or methanol plant, the load range for such a complex starts with approximately 300MW and may easily go up to 2 or 3 GW and more.

These new electrical loads are of a large magnitude, potentially accounting for 30 – 50% of the installed renewable energy capacity. This will undoubtedly require a thorough examination by the grid operators, who have extremely stringent grid codes for the behavior at battery limit.

Compared to a conventional plant, this is a significantly larger total plant load. The utility company must simulate these loads in conjunction with its grid to ensure proper and non-disturbing operation within the grid at all times. To assist the utility with this task, the large power electronic components and the balance of the plant complex must be modeled in specialized EMTP software tools.

These software models must also reflect the transient behavior of the equipment during various load conditions (following the availability of renewable energy), normal ramp up / ramp down transients and FRT situations as described above. This may result in the definition of operating regimes (support by the various process providers, e.g. provider of electrolysis technology), considering normal operation as well as process upset conditions or refurbishment / maintenance works.

These EMTP tools are new for the chemical industry but well accepted and widely used in the electrical utility industry.

All large power electronic systems such as the anticipated rectifier systems, large drive systems, harmonic filter and power factor improvement systems, are to be modeled in these tools. As these tools provide a dynamic image of the entire system, the in-depth knowledge for programming the models lies with the power electronic vendor. Generic models as they are used in standard software for electrical grid calculation are not sufficient for this task.

Challenges in this respect are the early availability of these software models, especially during an early phase, when no equipment has been purchased yet. Also, for the rectifier manufacturers, these tools are fairly new and most of the manufacturers have to invest a lot of effort into developing them prior to having a contract. Moreover, an additional party now enters the team: the grid operator or a contracted consulting company. This might result in numerous design iterations until the system is set up to full satisfaction.

VIII. Parameters and Production Capabilities of an AEL Electrolyzer

In the following, we present the technical parameters of an AEL electrolyzer, as it is currently used in the realization of various projects for hydrogen production.

- Nameplate capacity: 4000 Nm³ Hydrogen / hour at atmospheric pressure
- The electrolyzer can be constantly operated in a range of 10% - 100%

To satisfy process requirements, ramp up and ramp down times must be obeyed to comply with process temperature and pressure limits. These ramp up and ramp down times must be such that they can follow the needs for fast reaction in renewable energy grids.

Being a first of its kind unit, a certain safety margin for the electrical parameters was required, which resulted in the following design parameters for the rectifier system of one electrolyzer:

- Rated DC current: 34,5 kA
- Rated DC voltage: 675 V

Without going into the chemical details, here are the production details and electrical consumption figures of one such electrolyzer:

- 4000Nm³/h equals to 360kg/h ➔ 24h x 360kg/h = 8.634kg/day = 8,64mtpd of Hydrogen H2 equivalent to 285MWh (1kg H2 = 33kWh)
- These can be converted to 48,1mtpd of Ammonia NH3
- Electrical consumption just for electrolysis 20MW/h x 24h = 480MWh electrical energy per day

IX. Applications

A. Large scale hydrogen production for downstream ammonia plant, powered solely by PV and wind energy

In the following example, thyssenkrupp nucera was responsible for the supply of electrolyzers and rectifiers for a large green ammonia plant that converts hydrogen to green Ammonia for further transport worldwide.

Main technical data for the complex are about 600ton/day of hydrogen. Based on this production figure, the following quantity of electrolyzers (Elo) would be required.

600mtpd H2 / 8,64mtpd H2 / Elo = 70 Elos

energy consumption of 20MW x 70 Elo = 1.400MW = 1,40GW

All this is based on 100% full-load operation of the 70 Electrolyzers for 24/7 over the year. Due to the nature of the renewable resources, this is not possible. Especially the part of PV is very much fluctuating as it follows the night and day changes. These facts plus the regular maintenance and/or refurbishment of membranes on the electrolyzer units, as well as required overproduction to feed into intermediate H2 storage, led to the total amount of more than 100 installed electrolyzer units. With this number of electrolyzers, just the electrical power for full load is beyond 2.000MW = 2,0GW at the electrolyzer.

This electrolysis as well as the downstream ammonia plant including the associated off sites / utilities shall be supplied by a purely renewable power grid of approximately 4GW capacity, comprising of dedicated onshore wind farms of about 1,6GW and PV parks of 2.4GW photovoltaic power. In addition, a rather weak tie connection to a conventional power grid shall be established, but this must not be used for production purposes. These two sources will be connected by 380kV OHT lines. For grid support purposes, large BESS (battery energy storage systems) will be installed as well. As the entire design of this energy system was not in the scope of thyssenkrupp nucera, details are not available, however, a conceptional grid diagram is shown below.

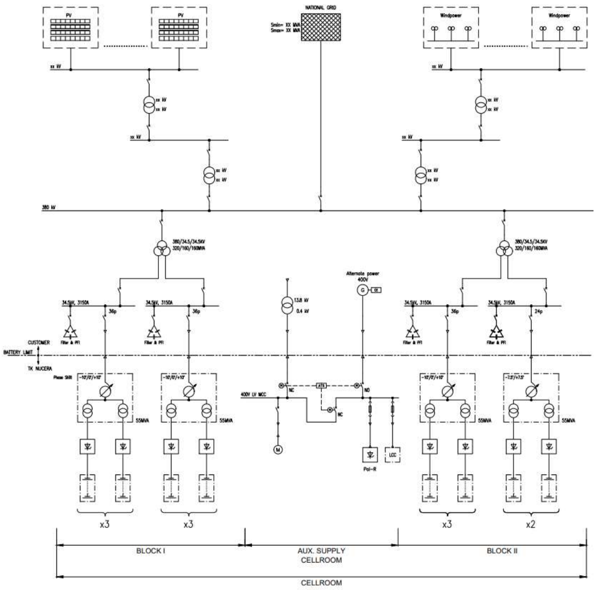


Fig. 25: Conceptional SLD for one out of five cellhouses, each with 22 electrolyzers [6]

Following the concepts described in chapter V, section D, each of the 33kV busses feeds three 1/2/2/2 units, except bus 4 which only feeds two. Each of these units has 12-pulse feedback to the feeding bus. The three autotransformers with OLTC on one 33kV bus are phase shifted, which results in a 36-pulse feedback to one 33kV bus, respectively 24 pulses for bus 4. Fig 25 shows one cellhouse, the entire complex comprises five such cellhouses.

B. H2 usage for conventional steel production

In the following scenario, we are going to replace the annual amount of steel produced by a large European steel manufacturer in a conventional furnace smelter process with an environmentally friendlier process of direct reduction.

This direct reduction process avoids the coal and coke-operated blast and blast oxygen furnaces, both large CO2 emitters, and replaces it with a gas-fired direct reduction process. The gas used in this case may be natural gas or hydrogen. Details about this technology are far beyond the scope of this paper. We will thus concentrate on the production of the required hydrogen for the reduction process. On average, an amount of 70kg of hydrogen per ton of steel shall be used.

From chapter VIII above, we know, that one electrolyzer can produce 8,634mtpd of hydrogen per day. Again, the electrical consumption for the electrolysis process alone amounts to 480MWh / day.

The average annual steel production is appr. 11Mio tons. This results in an overall hydrogen demand of

- 11.000.000 x 0,070tons H2 = 770.000tons H2/year
- With the daily production of one electrolyzer we could produce 8,634mtpd x 365day = 3.151 tons H2 / year.

Applying this figure to the annual requirement of 770.000 tons H2 / year results in 244 electrolyzers. As for the previous example, all this is only true for 24/7 full-load operation over the year. Assuming an overcapacity of approximately 20 - 25% for intermediate storage, regular maintenance and refurbishment yields 300 electrolyzers.

With the nameplate rating of 20MW / electrolyzer, the electrical consumption just for the electrolysis process amounts to 6.000MW = 6GW.

Producing this energy with 10MW wind turbines yields 600 wind turbines to be built.

As previously stated, this is just the electrical load requirement for the electrolysis plant, additional electrical power will be required for the electrical arc furnaces and all other ancillary plants around a steel mill.

X. CONCLUSIONS

This paper presents an overview and first insights into the challenges of large-scale hydrogen electrolysis projects, ranging from electrolysis technology, main electrical components for electrolysis, rectifier systems, PFI and harmonic filter systems, and connection issues with the renewable energy grids. An overview single line of an ongoing project is presented, as well as a possible scenario for hydrogen needs in a direct reduction-based steel production.

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XII. VITA

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